REPETITIVE HIGH CURRENT OPENING SWITCH

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Abstract

This paper describes a repetitive high current opening switch designed to discharge inductive energy stores. The switch employs a rotating shorting bar which electrically connects two stationary brush modules. As the shorting bar simultaneously sweeps across the finger contacts of each brush module, the switch is closed and conducts current. As the ends of the brush modules are approached, the switch resistance increases and the resulting voltage commutates current into the load. The rotating shorting bar and brush modules are positioned very close to the load to reduce the switch loop inductance and minimize the commutation energy which the switch dissipates. Unlike other rotary switch designs, only a portion of the brush modules conduct current at any given time. This decreases the duty on the brush contacts and increases switch life.

Introduction

To discharge an inductive energy store, an opening switch is required. The opening switch conducts current as the inductor charges and then quickly opens to commutate current into the load. While opening, the switch must be able to dissipate the commutation energy associated with the opening process and minimize switch degradation due to joule heating and arcing. Since the commutation energy is proportional to the switch loop inductance, a low inductance configuration is essential. An even greater challenge than a low inductance design is the ability to switch repetitively.

An in-house effort at Wright-Patterson AFB has been under way to demonstrate an electromechanical opening switch concept. The concept was conceived in 1985 (patent pending) and a test rig was built in late 1986 to demonstrate concept feasibility on a small scale. The opening switch test rig was designed to switch 10 kA at a maximum switching frequency of 10 Hz.

Switching Concept

Figure 1 depicts the opening switch concept. Brush modules are mounted on bus bars which are physically separated. The brush modules are crescent-shaped and protrude out from the bus bars. A rotating disk which has a conductive diametric strip on its face (shorting bar) is loaded against the brush modules and shorts the modules together. When the switch is closed (Figure 1-A), current flows from the positive bus bar and brush module thru the shorting bar to the negative polarity of the switch. As the disk continues to rotate, the shorting bar eventually slides to the edges of the brush modules (Figure 1-B). The reduced contact area increases the switch resistance. The resulting voltage commutates current out of the switch and into the load which is connected in parallel (not shown). Once the switch current goes to zero, the shorting bar aligns itself between the brush modules, maintaining an "opened" state (figure 1-C). Further rotation of the disk re-establishes contact between the brush modules and the shorting bar, and the switching cycle repeats.

The switch design has several advantages. First, only the portion of the brush modules in contact with the rotating shorting bar conduct current while the switch is closed. This reduces the duty which each of the brush contacts experience while the switch is on. Since the brush contacts are the most critical elements of the switch, reduced duty will result in a longer switch lifetime. The rotating shorting bar, however, does continuously conduct current while the switch is closed. Since the shorting bar is part of a thick conductive disk, the large thermal mass provides an excellent heat sink and conduction path to dissipate on-state resistive losses.

Furthermore, the load is closely integrated with the switch to minimize switch loop inductance. Switch loop inductance is determined by the current loop formed as current commutates from the switch into the load. If this loop is minimized, the energy which it stores (commutation energy) is also minimized. Since the commutation energy must be dissipated by the switch, minimizing switch loop inductance reduces switch degradation due to joule heating and arcing and increases switch lifetime.

Also, as the switch is scaled to higher current levels, the annular contact area of the brush module increases in proportion to the square of the length of the shorting bar. To take advantage of the increased contact area, various shorting bar shapes could be implemented, i.e., wider, non-rectangular, etc.

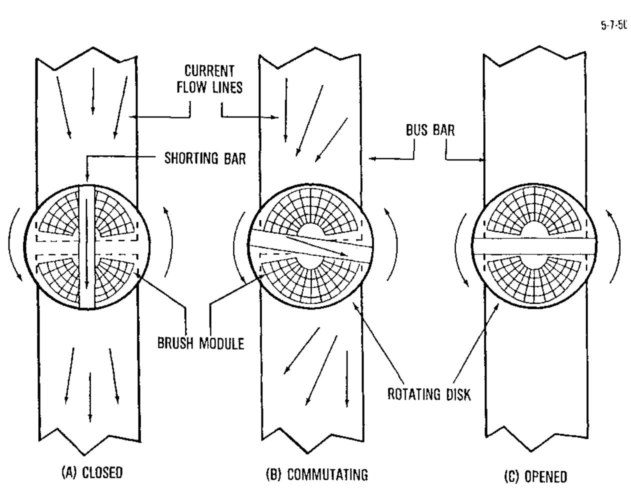

Figure 1. Repetitive high current opening switch concept.

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14. ABSTRACT

This paper describes a repetitive high current opening switch designed to discharge inductive energy stores. The switch employs a rotating shorting bar which electrically connects two stationary brush modules. As the shorting bar simultaneously sweeps across the finger contacts of each brush module, the switch is closed and conducts current. As the ends of the brush modules are approached, the switch resistance increases and the resulting voltage commutates current into the load. The rotating shorting bar and brush modules are positioned very close to the load to reduce the switch loop inductance and minimize the commutation energy which the switch dissipates. Unlike other rotary switch designs, only a portion of the brush modules conduct current at any given time. This decreases the duty on the brush contacts and increases switch life.

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Opening Switch Test Facility

Figure 2 depicts the Opening Switch Test Facility in the High Power Laboratory located in the Aero Propulsion Laboratory at Wright-Patterson AFB, Ohio.

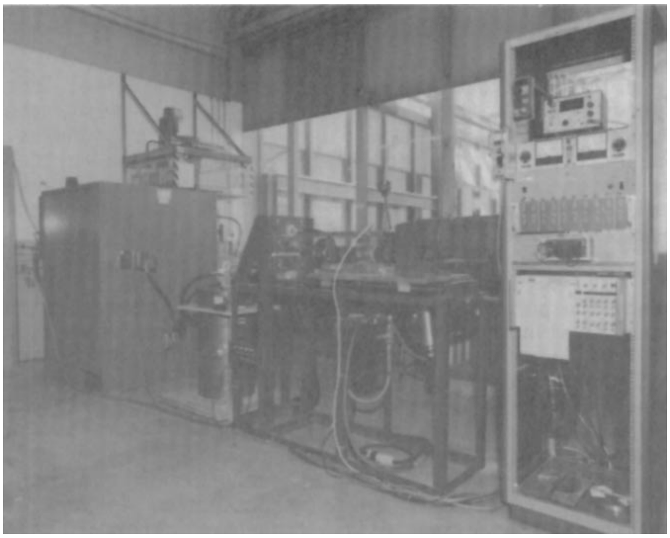

Figure 2. Opening switch test facility including (left to right) power supply, coil, opening switch test rig, and instrumentation.

Power Supply

The 5 MW power supply originally scheduled to test the opening switch to 10 kA is temporarily disconnected. Therefore, a 160 kW power supply was obtained and is pictured on the left side of Figure 2. The power supply input voltage is 440 V, 3 phase, 60 Hz and draws 300 amps. The input is then transformed and rectified to produce a 4 kA 40 V output.

Coil

The inductive energy store (just right of the power supply) is a single layer solenoid 0.4 m in diameter and 0.8 m long. It has 56 turns of 1.27 cm square copper bar. The computed inductance is 500 uH and the resistance is 7.85 mΩ. The computed time constant is 64 mS and it stores 18 kJ at the design current of 8.5 kA.

Opening Switch Test Rig

The opening switch test rig (Figure 3) consists of a drive and actuation assembly, rotor and brush modules.

Drive and Actuation Assembly: The drive consists of a variable speed constant drive motor overhung on a 5:1 speed reducing gearbox. The maximum rotor speed is 300 rpm, which equates to a switching frequency of 10 Hz. A remote control unit can adjust the switching frequency from 1-10 Hz. The rotor and associated drive components are mounted on a table which rides on a set of linear bearings. An air piston connects the table to the test rig frame. To load the rotor against the brush modules for switch operation, the air piston is actuated with a regulated amount of air to control rotor loading.

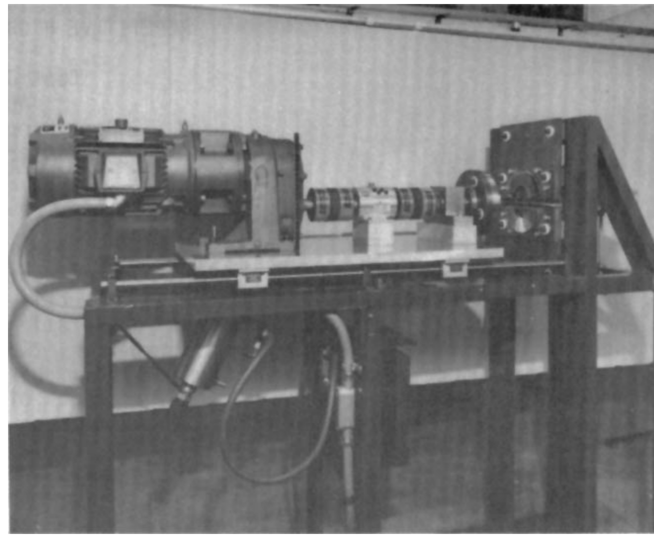

Figure 3. Opening switch test rig including (left to right) motor drive, torque transducer rotor, brush modules and bus bars.

Rotor: The rotor (Figure 4) is a 2.54 cm thick copper disk with a 20.32 cm diameter. The brush modules contact the face of the disk during switch operation. The face of the rotor is machined and filled with an insulator such that the only conductive section is a diametric strip, called the shorting bar. Insulators used to date include epoxy and teflon. The shorting bar can be tailored to adjust the commutation voltage developed as the switch opens. The conductive rotor is bolted to and electrically insulated from a mounting plate which is connected to the drive system.

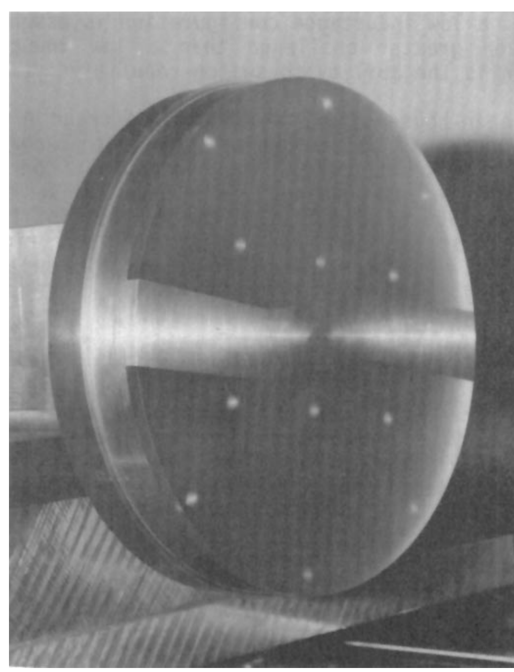

Figure 4. Rotor with mounting plate (left) and copper disk (right). Non-conductive inserts are machined into the copper disk face (top and bottom) to expose the shorting bar.

Brush Modules: The brush module (Figure 5) contact area is crescent-shaped and consists of a series of copper leaves 3.8 cm long. The leaves are angularly displaced from each other by 1.5 degrees. Each leaf has 30 contact fingers resulting in over 3,000 contact points per polarity. The leaves are canted at 30 degrees to allow for individual spring loading of each finger. The brush modules bolt directly onto the positive and negative bus bars which are space 2.54 cm apart. The spacing of the bus bars and geometry of the brush modules allows a 90% duty cycle during switch operation.

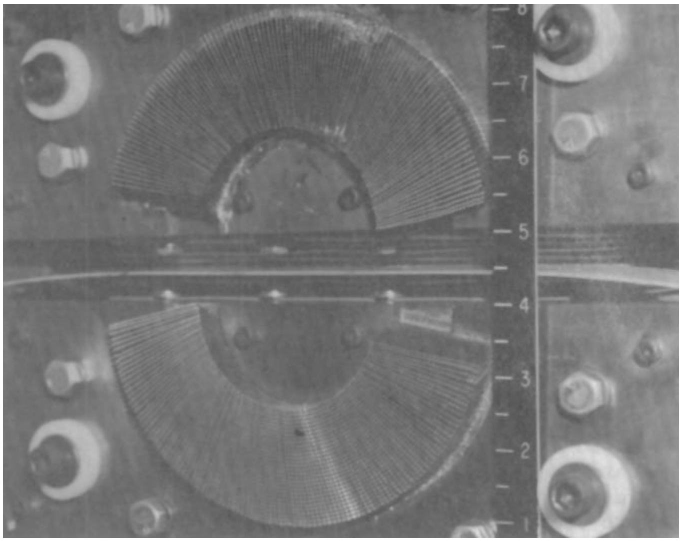

Figure 5. Positive (top) and negative (bottom) brush modules. Load is positioned between the brush modules and extends to the rear.

Load

The load is a series of stacked stainless steel plates. The plates can be arranged to vary the load resistance from 1 to 10 mΩ, while providing a very low inductance. The load bolts onto the bus bars between the brush modules (Figure 5).

Instrumentation

A Honeywell Visicorder is used to record the data. A current shunt is used to measure circuit current. Rogowski coils with active integrators measure current in the load and switch. Switch and load voltages are measured using a differential amplifier. Torque is measured with a rotary torque transducer. A thermocouple is positioned on each of the commutating brush leaves and hooked to an Omega digital thermometer. The instrumentation rack is pictured on the right side of Figure 2.

Preliminary Test Results

Mechanical Tests

To reduce frictional heating and drive power requirements, the non-conductive areas on the rotor face are machined to taper away from the shorting bar. This reduces the loading on those finger contacts which are not conducting current during switch operation. A 20 mil taper on the epoxy-filled rotor reduced drive power requirements by a factor of 2.5.

Material selection for the non-conductive sections of the rotor must focus on a material which operates at elevated temperatures and has a low wear rate and low coefficient of friction. Thermal plastics are good candidates for the insulator and much of the future testing will concentrate on teflon which is readily available and inexpensive.

Test stand calibration indicates a rotor speed of 30 rpm per 1 Hz of switching (300 rpm max), 10.5 pounds force for every psi of air in the air piston during actuation, and a finger deflection of about 10 mils during switch operation.

Electrical Tests

The switch has conducted over 4,000 amps for several seconds in a static mode (non-rotating, non-switching) with no visible sign of degradation. As the shorting bar was aligned in various positions, the switch resistance varied from 10 to 20 uΩ. The switch resistance was also dependent on contact preparation and run-in time as expected.

Although an exact calculation of switch inductance has not been determined from a plot of switch current during commutation, preliminary measurements with an impedance bridge indicate an inductance value of about 20 nH.

The switch has successfully stood off 3 kV during a hipot test. The packing factor varies across the brush module, but an average packing factor of .2 has been computed. The design current density is 8 kA/cm^2.

Conclusion

Although switching tests have not been conducted, no limitations have been identified which would preclude a successful test program. The low resistance and inductance measurements are also very encouraging.

Future tests will evaluate a slotted rotor which will increase commutation voltage by a factor of 100. Switching tests of up to 10 kA at 10 Hz will also be conducted.